Application of Hydrodynamics and Dynamics Models for Efficient Operation of Modular Mini-AUVs in Shallow and Very-Shallow Waters

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LONG-TERM GOALS

The long-term goal of this research is to contribute to improvements in design and motion-control of small autonomous underwater vehicles, including multiple-vehicle operations and particularly for missions in wave-energetic shallow and very-shallow waters, based on rigorous dynamic and hydrodynamic analyses and modeling.

OBJECTIVES

The objective of the research is to carry out nonlinear dynamics and hydrodynamics analyses of small and modular mini-AUVs and determine their vehicle-stability, -maneuverability and motion-response characteristics for a range of missions, vehicle-configurations and sea states, and thereby contribute to improving the efficacy and reliability of modular AUVs.

APPROACH

The research investigates two main aspects of dynamics and hydrodynamics of underwater vehicles; namely, [i] determination of hydrodynamic forces on an underwater vehicle including effects of viscosity, large-amplitude body motion and surface waves, and [ii] analysis of motion response, stability and maneuverability of underwater vehicles subjected to the hydrodynamic forces. The hydrodynamic and dynamic simulations are carried out for a range of ambient and vehicle parameters, in order to identify key factors affecting the performance of underwater vehicles.

Computationally efficient and robust algorithms have been specially developed for the present analyses. The hydrodynamic forces are computed by solving the governing nonlinear equations using finite-difference and boundary-integral methods. The inviscid nonlinear wave-AUV interaction problem is solved and wave-radiation and –diffraction forces determined using a boundary-integral method based on the mixed *Eulerian-Lagrangian* formulation [6][8][10]. As, in the regimes of validity, linear and inviscid calculations are straightforward and economical, boundary integral methods based on simple source distribution and linearized boundary conditions have also been developed[8]. Approximate linear and inviscid methods, as that based on the *Froude-Krylov* method[7][9] formulated in moving coordinates are also considered, to determine the diffraction forces due to long and small-amplitude waves on small underwater vehicles.

The viscous wave-AUV hydrodynamics problem, *ie.,* Navier-Stokes equations together with viscous free-surface conditions, is solved in primitive variables[4] using boundary-fitted coordinates based finite-difference method [2][3][5] to determine drag, radiation and diffraction forces. Turbulence models, such as Baldwin-Lomax, are implemented for the solution of Reynolds-Averaged Navier-Stokes equations.

The rigid-body equations of AUV motion, subject to hydrodynamic and propulsion forces, are solved to determine the open-loop vehicle stability, maneuverability and motion response for various vehicle configurations and operating conditions[1] . Based on the dynamic simulation software developed for the analysis, optimal configuration of an AUV and viability of a mission in the given sea state can be determined *a priori*.

In order to validate and complement the numerical algorithms used for the determination of hydrodynamic forces, a model tests are underway at the SeaTech facility of Florida Atlantic University in the recently-completed wave-current tank equipped with PIV and force-measurement systems. Field measurement of vehicle motions and sea states made during sea trials of Florida Atlantic University's AUVs will be used to assess the predictive capability of the AUV hydrodynamics/dynamics model.

Complementing the proposed research on the vehicle dynamics, a simple hydrodynamics-based algorithm was developed to model the thrust and torque of the AUV propeller. The algorithm is based on the blade-element method[11] with lift and drag coefficients of the blade sections specified from experimental data. The algorithm can be used for the design of thrusters for the AUV and to determine thrust and torque as functions of rpm, pitch angle and forward speed.

WORK COMPLETED

The efforts performed in fiscal year 2002 (01 October 2001 to 30 September 2002) are as follows:

1. Boundary integral methods based on the mixed *Eulerian-Lagrangian* formulation for nonlinear analysis and on the simple-source formulation for linear frequency-domain analysis have been developed and wave hydrodynamic forces determined for submerged bodies, including the *Morpheus* AUV, for a range of parameters including depth of vehicle submergence[8].

2. A fully-implicit three-dimensional finite-difference algorithm has been developed to analyze viscous flow about underwater vehicles and determine the hydrodynamic forces.

3. Linear diffraction forces on *Morpheus* AUV for a large parameter range of heading angles, speeds and depths have been computed based on the *Froude-Krylov* method.

4. The wave tank at the FAU's SeaTech facility has been equipped with appropriate equipment such as wave-maker, force and wave measurement systems, and PIV to conduct model tests. A force balance system has been developed to measure diffraction forces on a submerged body. A better "beach" has been designed and built for the wave tank.

5. Computation of hydrodynamic coefficients of underwater vehicles operating near the free surface including free-surface effects, as customarily done in Naval Architecture[12] through turning, spiral and zigzag tests, is in progress.

6. Computation of large-amplitude wave diffraction forces on an AUV using the mixed Eulerian-Lagrangian algorithm is also underway.

7. The simulation of nonlinear motion response of AUVs in energetic waves, using the above computed coefficients and forces, is in progress.

8. The Baldwin-Lomax turbulence model has been implemented in the viscous-flow solver and preliminary turbulent flow results obtained. Eddy-viscosity models, such as the Baldwin-Lomax model, provides a convenient closure to the RANS equations, as it has the same form as the Navier-Stokes equations. The model does not require significantly more CPU time, as no further transport equation is added to the formulation. Adding turbulent viscosity to kinematic viscosity in RANS equations also increases stability of numerical computations.

RESULTS

Representative results of our efforts during the fiscal year 2002 are dicussed in this section. The numerical computations are made for the *Morpheus* AUV of Florida Atlantic University (see Fig.1).

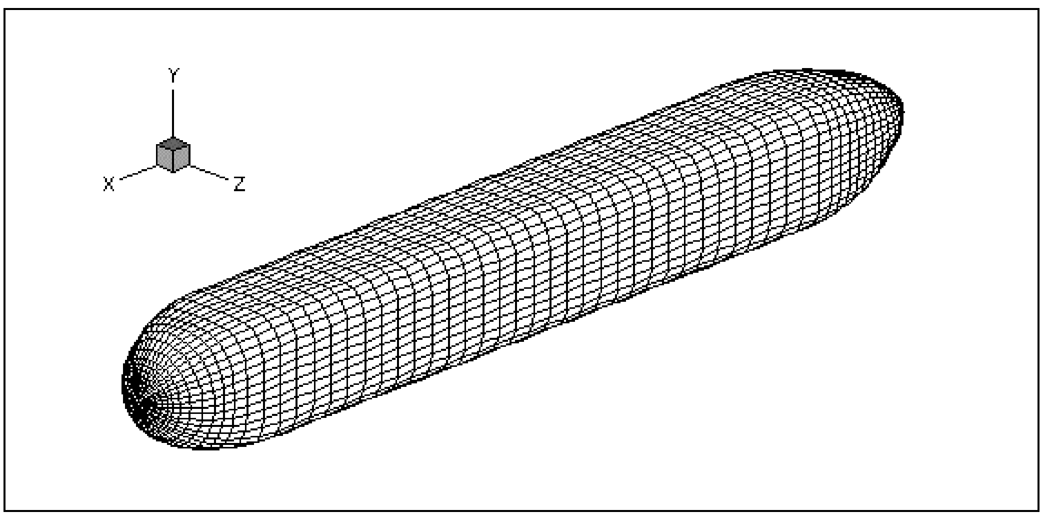

Fig. 1: Modular AUV Morpheus of Florida Atlantic University

Turbulent-Flow Analysis: Three-dimensional, large Reynolds-number viscous flow results are obtained through a fully-implicit finite-difference computations. Baldwin-Lomax turbulence model is used for the solution of the Reynolds-Averaged Navier-Stokes equations. Fig.2 shows the horizontal component of mean velocity and streamlines, and the pressure field at a Reynolds number of $2x10^6$. One can clearly observe boundary-layer separation, and formation of primary and secondary vortices at the stern and the reattachement of the mean flow downstream in the wake. The dynamic pressure field given in Fig. 2, illustrate the origin of the form drag due to the separation.

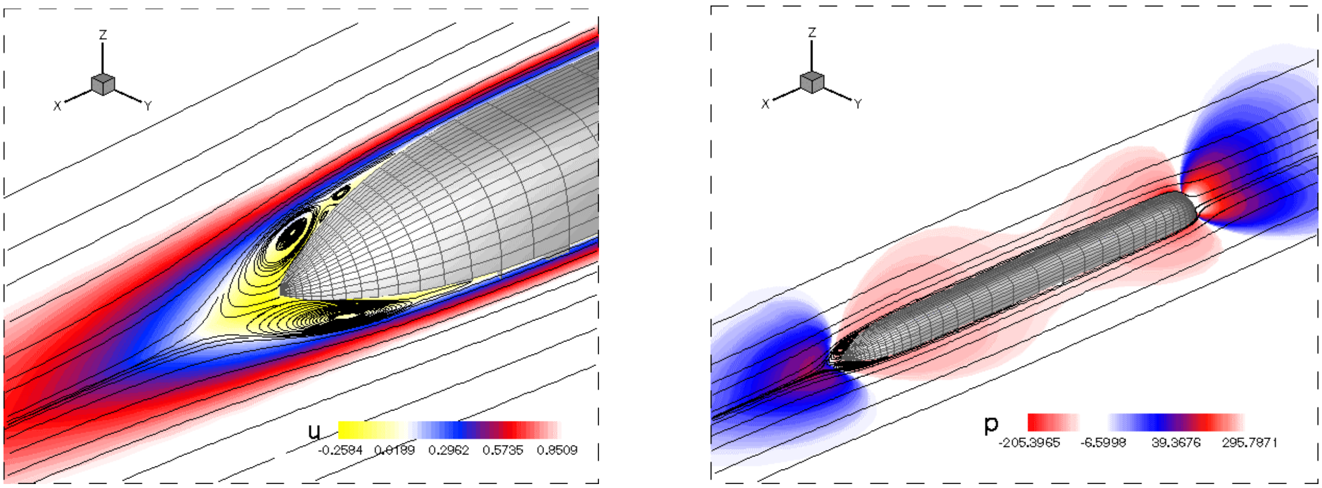

Fig. 2: Horizontal velocity (left) and dynamic pressure field (right) at Re=$2x10^6$. See text for details.

Boundary-Integral Analysis: Using the boundary-element method based on Longuet-Higgins and Cokelet's mixed Eulerian-Lagrangian formulation developed for the the analysis of nonlinear wave-AUV interactions, hydrodynamic forces and coefficients for the *Morpheus* AUV are computed [8]. The hydrodynamic forces are computed using the hydrodynamic coefficient per *added-mass theory*[7]. The instantaneous free-surface deformations associated with heave, surge and sway motions of the *Morpheus* AUV are given in Fig. 3 which reveals the radiation of complex wave patterns associated with Morpheus motion near the surface.

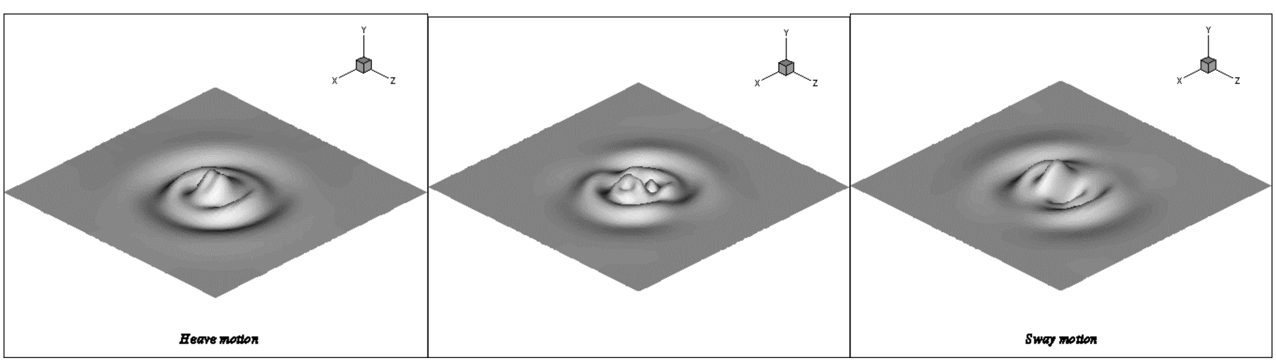

Fig.3: Free-surface deformations corresponding heave(left), surge(middle) and sway(right) oscillations of Morpheus AUV at nondimensional depth 0.75, amplitude of oscillation 0.05.

IMPACT/APPLICATIONS

1. The hydrodynamic analyses contribute to a better understanding of the fundamental physics of nonlinear wave-body interactions and vehicle response in shallow and very-shallow waters.

2. The nonlinear dynamic simulations of vehicle motions help to identify the key mechanisms affecting and contributing to marine-vehicle stability. The analysis thus contributes to improvements in vehicle design and to the development of optimal configurations and controllers of small modular underwater vehicles.

3. The research has also contributed to identifying effects of surface waves and viscosity on the hydrodynamic coefficients of underwater vehicles.

4. Upon completion of the intended long-term goal, the methodologies developed in the present research would prove to be a accurate and reliable alternative to the expensive tow-tank and field measurements of hydrodynamic coefficients of marine vehicles.

TRANSITIONS

The results and findings of the hydrodynamics and rigid-body dynamics analyses are communicated to the AUV researcher Dr. Edgar An, Department of Ocean Engineering, Florida Atlantic University who is involved in the development of simulation software and control algorithms for AUVs. Dr. An has also served in the thesis committees of graduate students involved in the present research under the guidance and supervision of the PI.

PUBLICATIONS

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